DOE/PC/95151--T6

TECHNICAL PROGRESS REPORT

for the Third Quarter

(April, 1996 to June 30, 1996)

POC-SCALE TESTING OF A DRY TRIBOELECTROSTATIC SEPARATOR FOR FINE COAL CLEANING

by

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Contract Number:
DE-AC22-95PC95151

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ABSTRACT

The Pittsburgh Energy Technology Center (PETC) developed a triboelectrostatic separation (TES) process which is capable of removing mineral matter from coal without using water. A distinct advantage of this dry coal cleaning process is that it does not entail costly steps of dewatering which is a common problem associated with conventional fine coal cleaning processes. It is the objective of this project to conduct a series of proof-of-concept (POC) scale tests at a throughput of 200-250 kg/hr and obtain scale-up information. Prior to the POC testing, bench-scale test work will be conducted with the objective of increasing the separation efficiency and throughput, for which changes in the basic designs for the charger and the separator may be necessary. The bench- and POC-scale test work will be carried out to evaluate various operating parameters and establish a reliable scale-up procedure. The scale-up data will be used to analyze the economic merits of the TES process.

At present, the project is at the stage of engineering design (Task 3). Work accomplished during this reporting period include the construction of a Faraday Cage for measurement of particle charges (Subtask 3.1), construction of the a bench-scale triboelectrostatic separator (Subtask 3.2) and development of a theoretical model for predicting motion of charged particles in a non-uniform electrostatic field (Subtask 3.2). This model will be useful for designing the POC module.

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INTRODUCTION

Numerous advanced coal cleaning processes have been developed in recent years that are capable of substantially reducing both ash- and sulfur-forming minerals from coal. However, most of the processes involve fine grinding and use water as cleaning medium; therefore, the clean coal products must be dewatered before they can be transported and burned. Unfortunately, dewatering fine coal is costly, which makes it difficult to deploy advanced coal cleaning processes for commercial application.

As a means of avoiding problems associated with the fine coal dewatering, the Pittsburgh Energy Technology Center (PETC) developed a dry coal cleaning process, in which mineral matter is separated from coal without using water. In this process, pulverized coal is subjected to triboelectrification before being placed in an electric field for electrostatic separation. The triboelectrification is accomplished by passing a pulverized coal through an in-line mixer which is made of copper, whose work function lies in-between those of carbonaceous material (coal) and mineral matter. Thus, coal particles impinging on the copper wall loses electrons to the metal, thereby acquiring positive charges, while mineral matter impinging on the wall gains electrons to acquire negative charges. The triboelectrostatic separation (TES) process has been tested successfully on bench-scale. The results obtained at PETC showed that it is capable of removing more than 90% of the pyritic sulfur and 70% of the ash-forming minerals from a number of eastern U.S. coals. It is necessary, however, to test the process on a proof-of-concept scale so that appropriate scale-up information is obtained. Furthermore, it is necessary to increase the throughput of the TES process by improving the design for the electrostatic separation system.

The laboratory-scale batch TES unit used by PETC relied on adhering charged particles on parallel electrode surfaces and scraping them off. Therefore, its throughput will be proportional to the electrode surface area. If this laboratory device is scaled-up as is, it would suffer from low throughput capacity and high maintenance requirement. In general, surface area-based separators (e.g., shaking tables, magnetic drum separator, electrodynamic separator, etc.) have lower throughput capacities than volume-based separators (e.g., flotation cell, dense-medium bath, cyclones, etc.) by an order of magnitude. Furthermore, the electrodes of the laboratory unit need to be cleaned frequently, creating a high-degree of maintenance requirement if it is scaled-up to a commercial unit. The bench-scale continuous TES unit developed at PETC, on the other hand, separates positively and negatively charged particles by splitting the gaseous stream containing these particles in an electric field by means of a flow splitter, so that the oppositely charged particles can be directed into different compartments. This device is fundamentally different from the laboratory unit in that the former is a volume-based separator, while the latter is a surface area-based separator. The bench-scale unit is referred to as *entrained flow* separator by the in-house researchers at PETC. Thus, the entrained flow TES unit is a significant improvement over the laboratory unit with regard to throughput capacity.

In the present work, the entrained flow separator will be scaled-up to proof-of-concept POC-scale. However, the parallel plate electrodes will be replaced by a pair of circular electrodes, for which there are two advantages. First, the circular electrodes provide a non-uniform electric field (and, hence, a field gradient), which will be conducive for improving the separation of oppositely charged particles from each other. Second, the electrode will be rotated so that fresh electrode surfaces can be exposed. This new design is similar to the open-gradient magnetic separator developed by Oak Ridge National Laboratory during the early 1980s. Therefore, the new design may be referred to as *open-gradient* triobelectrostatic separator.

OBJECTIVES

It is the objective of the project to further develop the TES process developed at PETC through bench- and POC- scale test programs. The bench-scale test program is aimed at studying the charging mechanisms associated with coal and mineral matter and improving the triboelectrification process, while the POC-scale test program is aimed at obtaining scale-up information. The POC-scale tests will be conducted at a throughput of 200-250 kg/hr. It is also the objective of the project to conduct cost analysis based on the scale-up information obtained in the present work.

Specific objectives of the work conducted during this quarter were: i) to design and set-up an apparatus for studying triboelectrification mechanism with an objective of maximizing separation efficiency (Task 3.1), ii) to complete construction of the bench-scale (1 kg/hr) triboelectrostatic separator (Task 3.2), and iii) to continue development of the fundamental model for predicting the motion of charged particles in a non-uniform electrostatic field (Task 3.2).

WORK DESCRIPTION

Task 3.1: Tribocharger Tests

As will be shown later in this report, separation efficiency of the TES process depends critically on the surface charges of the particles involved. In general, the larger the difference between the charges of particles to be separated, the higher the separation efficiency. It is, therefore, the objective of this subtask to design efficient charger for the triboelectrostatic separator. To meet this objective, the following R&D activities will be undertaken.

- studies of charging mechanism
- evaluation of charger design

- evaluation of charger materials
- development of design/scale-up criteria

During the current reporting period, charging mechanisms have been studied. However, much of our efforts have been concentrated on developing an appropriate technique for charge measurement. Two different techniques were considered. One is the technique developed by Mazumder, in which charged particles are placed in an electromagnetic field, while monitoring the trajectories. The other is the method of using Faraday cages. The former may be more accurate than the latter; however, it requires a more sophisticated and costly equipment. Furthermore, this technique cannot be used for measuring the charges of particles larger than 60 μm. Although most of the TES tests were conducted on micronized coal samples at PETC, it is hoped that the POC module to be developed in the present work can be tested on coarser particles, (e.g., PC-grinds). It was, therefore, decided to use a Faraday cage to measure particle charges in the present work.

Figure 1 shows the Faraday cage used for measuring charges of particles, and Figure 2 shows how it is connected to an electrometer (Keithly Model-642) and a data acquisition system. The Faraday cage consists of inner and outer cages made of copper. The inner copper cage is electrically connected to the electrometer through a coaxial cable, while the outer cage is grounded. Both the inner and outer cups have copper lids to prevent the measurement being affected by the stray electric fields from the surroundings. This design is different from what is generally reported in the literature. Without the lids, the measurement suffered from too much noise. The particles are delivered to the inner cage through a small copper tubing, which is an extension of the inner cup. It is necessary to make the copper tubing as part of the inner cage. Otherwise, particles colliding on the inner wall of the copper tubing can acquire additional charges, causing a source of error.

Figure 3 illustrate the mechanisms involved in the charge measurement using the Faraday cage. Consider particles touching the walls of the inner cup (Figure 3a). Let us assume that the particles are charged negatively, in which case the free electrons of the particles will flow from the particle surface to the walls, resulting in a flow of electric current from the Faraday cage to the electrometer. Consider also the case of the negatively charged particles not touching the walls (Figure 3b). In this case, the negatively charged particles will polarize the inner copper cup in such a way that the inner wall is positively charged while the outer wall is negatively charged. The free electrons will flow from the negative charge sites of the inner wall to the electrometer, causing a current. Thus, the net results are the same in both cases, i.e., the presence of negatively charged particles will result in a current flowing from the Faraday cage to the electrometer.

Figure 4 shows a print out from our data acquisition system connected to the Faraday cage. The result was obtained with a sample of quartz particles (D_{50} = 60μm). It shows that the quartz particles are negatively charged. The charge is dissipated within 180 seconds since the particles are placed in the Faraday cage. Figure 5 shows the result obtained using 2.5 g of a coarse Pittsburgh No. 8 coal sample (+65 mesh). As shown, the coal particles are positively charged with a charge density of 6.6×10^{-15} C/g. Figure 6 shows the result obtained using 4.5 g of finer coal particles. The current signals obtained are higher due to the larger amount of sample and the surface area. The charge density of the finer coal sample is 7.1×10^{-15} C/g. The results given in Figures 4-6 show the basis of the TES process, i.e., coal particles are separated from ash-forming minerals such as quartz due to the difference in particle charge. Maximizing the charge difference would increase its separation efficiency.

Now that the Faraday cage has been constructed and is functioning properly, the particle charging mechanisms will be studied in detail during the next reporting period. It is planned to investigate the following parameters:

- particle size
- rank
- intensity of agitation
- agitation time
- coal-to-particle ratio in feed
- charger material

All of these parameters are needed for designing efficient POC-scale TES unit.

Task 3.2 Separator Tests

The primary objectives of this subtask are i) to evaluate different bench-scale designs for the triboelectrostatic separator, and ii) to investigate the various operating parameters on separator performance. The information obtained from this task will be used for obtaining engineering guidelines for the design, manufacture, operation and optimization of the 200-250 Kg/hr POC unit. The bench-scale tests will be conducted using two different separators having nominal capacities of 1 kg/hr and 10-20 kg/hr. The performance data obtained fro these units will be used to develop scale-up criteria for POC unit.

A. Construction of a Bench-scale Separator

During the past quarter, a bench-scale TES separator has been constructed. Figure 7 shows a schematic representation of the separator. A coal containing mineral matter is pneumatically fed to an in-line mixer charger. When the particles exit the charger, coal particles will be charges positively while the mineral matter be charged negatively. The charged particles will pass through a collimator (flow straightner) and then through the uneven electric field created between two rotating circular electrodes. Positively charged coal particles are directed toward the negative electrode, while negatively charged mineral matter are directed toward the positive electrode. The splitter in between the two electrodes can be located in different positions to achieve some control of grade and recovery. The main advantage of this open-gradient separator concept is that the throughput is essentially proportional to the volume of the entrained flow. In addition, the rotating cylindrical electrodes are self-cleaning.

A bench-scale open-gradient TES unit is being fabricated and assembled. Figure 8 shows the photograph of the equipment. A power supply has been installed and hooked-up to the electrodes. It is capable of attaining a maximum applied voltage of 100 kV across the electrodes, i.e., +50 kV to the positive electrode and -50 kV to the negative electrode. The electrical circuit is being inspected by the Safety Department of the university. The only parts missing at present is the control panel and the collimator. We are also waiting a micronizer to be shipped to us from PETC. Dr. Dennis Finseth is making the necessary arrangement for the shipment. Until the micronizer is shipped, test work will be conducted using the samples pulverized by means of a hammer mill.

Because of the cylindrical electrode design, the bench-scale unit produces a non-uniform electrostatic field which is substantially different from the uniform fields generated by previous designs which utilized flat-plate electrodes. The non-uniform field induces an additional force on the particles that varies from the top to bottom of the electrodes. At present, the model is being used to investigate the motion of charged particles in the non-uniform electrostatic field. Eventually, the model will be used to study the impact of changes in electrical potential and drum diameter on separator performance.

b. Modeling of Electrostatic Separation

As part of the engineering design of a POC unit, a theoretical model has been developed. The force (F) acting on a particle in an electric field is given by the following relationship:

$$F = qE \qquad [1]$$

in which q is the net (free) charge of the particle and E is the field strength. Eq. [1] is valid for conventional electrostatic separators which provides uniform electric fields between two flat electrodes.

In a non-uniform electric field, such as the one created in an open-gradient TES unit (Figure 7) being developed in the present work, additional force due to field gradient must be considered. Thus, the total force acting on a particle in a non-uniform electric field becomes:

$$F = qE + kE\nabla E$$

where k is a constant and ∇E is the field gradient. The value of k varies depending on the size, shape, conductivity, and dielectric constant of the particles in the electric field. Let us consider an electric field created between two cylindrical electrodes of radii R_1 and R_2 (see Figure 9). The calculation of F may be simplified by treating the charges, q, of the electrodes as point charges located at A_1 and A_2. The potential, φ, at point M in space can then be calculated using the Coulomb's law:

$$\varphi = \frac{1}{2}\pi\varepsilon\varepsilon_0 q \ln\left(\frac{1}{r}\right) \qquad [2]$$

where ε_0 is the permitivity of vaccum ($8.854\text{x}10^{-12}$ Fm^{-1}) and ε is the dielectric constant of air which is unity.

Applying Eq. [2] for the point charges of q at points A_1 and A_2, the potential at an arbitrary point M becomes:

$$\varphi = \frac{\sigma}{2\pi\varepsilon\varepsilon_0} \ln\left(\frac{r_2}{r_1}\right) \qquad [3]$$

where σ is the linear charge density, and r_1 and r_2 are the distances between the two point charges A_1 and A_2 and the point M in space. From geometric considerations of the electrodes shown in Figure 9, one can readily derive the following relationship:

$$\varphi = \frac{\sigma}{2\pi\varepsilon\varepsilon_0} \ln\left(\frac{r_2}{r_1}\right) = \frac{\sigma}{2\pi\varepsilon\varepsilon_0} \ln \frac{\sqrt{(h_1 + a - x)^2 + y^2}}{\sqrt{(a - h_1 + x)^2 + y^2}} \qquad [4]$$

where

$$h_1 = \frac{D^2 + R_1^2 - R_2^2}{2D} \qquad [5]$$

$$h_2 = \frac{D^2 + R_2^2 - R_1^2}{2D} \qquad [6]$$

where D is the distance between the centers these two cylinders.

Eq. [4] can be differentiated to obtain field gradients in *x* and *y* directions as follows:

$$E_x = -\frac{\partial\varphi}{\partial x} = \frac{\sigma}{2\pi\varepsilon\varepsilon_0}\left[\frac{a - h_l + x}{(a - h_l + x)^2 + y^2} + \frac{h_1 + a - x}{(h_1 + a - x)^2 + y^2}\right] \qquad [7]$$

and

$$E_y = -\frac{\partial\varphi}{\partial y} = \frac{\sigma}{2\pi\varepsilon\varepsilon_0}\left[\frac{y}{(a - h_1 + x)^2 + y^2} - \frac{y}{(h_1 + a - x)^2 + y^2}\right]. \qquad [8]$$

Eqs. [7] and [8] may then be used to derive equations of motion in *x*-direction:

$$m\frac{\partial^2 x}{\partial t^2} = qE_x \qquad [9]$$

and in the *y*-direction:

$$m\frac{\partial^2 y}{\partial t^2}=mg+qE_x \qquad [10]$$

where m is the mass of particle under consideration, g is the gravitational acceleration, and q is the particle charge.

Eqs. [9] and [10] have been used in the present work to determine the trajectories of particles in the non-uniform electric field. A series of computer simulations were carried out using the geometrical constraints shown in Figure 10. Two electrodes of identical diameters (R) of 0.15 m were considered. The distance (D) between the centers of the two electrodes were 0.5 m, and the distance between the collection plate and the axis of the two electrodes (h) were 0.5 m. The potential difference between the two electrodes were 80 kV. Simulations were run for different particle charges (q/m) in units of C/Kg, initial positions (a and b), and different velocities. Under these conditions, the following boundary conditions can apply:

$$\left.\frac{\partial x}{\partial t}\right|_{t=0}=0 \ and \ x\big|_{t=0}=b \qquad [11]$$

for Eq. [9]. The boundary conditions for Eq. [10] are as follows:

$$\left.\frac{\partial y}{\partial t}\right|_{t=0}=V \ and \ y\big|_{t=0}=-a. \qquad [12]$$

In using the equations of motion (Eqs. [9] and [10]) derived in the present work for simulation, it is necessary to know the value of the charge (σ) on the surface of the electrodes used in the simulation. (This is because σ is an important parameter of Eqs. [7] and [8], which in turn are used in Eqs. [9] and [10].) In the present work, the value of σ was determined using the following relationship:

$$\mu=\varphi_1-\varphi_2=\frac{\sigma}{2\pi\varepsilon\varepsilon_0}\ln\frac{(h_1+a-R_1)(h_2+a-R_2)}{(R_1-h_1+a)(R_2-h_2+a)} \qquad [13]$$

in which μ is the difference in potentials, φ_1 and φ_1, at the closest distance between the two electrode surfaces while h_1, h_2, R_1, R_2 and a represent the geometric constraints of the electrostatic separator as shown in Figure 10. In electrostatic separation, the distance between two electrodes are usually set at a maximum distance where no spark occurs at a given applied potential. Under most conditions in air, sparks occur when μ exceeds certain critical value, which is determined by the following relationship:

$$\mu = l \times \left(4 \times 10^5 Vm^{-1}\right) \qquad [14]$$

where l is the closest distance between the surfaces of two electrodes and is given in units of meters. In the present simulation, l=0.2 m; therefore, μ=80 kV. Substituting this value into Eq. [13] along with the geometric constraints used in the simulation, one can obtain the value of σ.

Table 1 shows the results of the computer simulation conducted in the present work. The values of c in the table represent the deflection of particles from the vertical trajectory, which may

Table 1. Results of computer simulation based on the geometric constrains given in Figure 10

q/m (x 10^5)	a (m)	b (m)	V (m/s)	c (m)
1	0.15	0	0	0.18
1	0.15	0	1	0.11
1	0..15	0	3	0.04
1	0.15	0.04	0	0.19
1	0.15	-0.04	0	0.18
1.5	0.15	0	0	0.28
1.5	0.15	0	3	0.06
1.5	0.15	0	1	0.16
1.5	0.25	0	1	0.16

represent the selectivity of the TES process. An important conclusion that can be drawn from the simulation results is that as the feed velocity of particles increases, the deflection and, hence, the selectivity decreases; however, this problem can be minimized by increasing the charge of the particles. Therefore, it is of paramount importance to study the particle charging mechanisms and develop methods of maximizing the charge of coal particles. It should be pointed out also that the model developed in he present work is useful for optimizing the design of the bench- and POC-scale TES unit.

SUMMARY

The work performed during the current reporting period was concerned with Engineering Design (Task 3). As part of this task, tribocharging mechanism has been studied (Subtask 3.1). A major accomplishment made during the past quarter was that a Faraday cage has been built to measure the charges of particles. This device is equipped with a data acquisition system to achieve a high degree of accuracy and increase the speed of measurement. An advantage of using the Faraday cage is that the charge measurement can be conducted for a wide range of particle sizes. The results obtained to date are consistent with the data reported in the literature, i.e., Pittsburgh No. 8 coal particles are positively charges, while quartz particles are negatively charged.

As part of the Engineering Design work, a bench-scale TES unit has been constructed (Subtask 3.2). The design and fabrication are almost complete except the control panel and collimator. The electrical circuit is to be inspected by the Safely Department of the University. The design of the bench-scale unit is based on the open-gradient (or entrained-flow) concept, which should give a high throughput capacity. The throughput of the bench-scale unit is expected to exceed 10-20 kg/hr.

Under Subtask 3.2, a theoretical model for open-gradient TES unit has been developed. The model is capable of predicting deflection of charged particles as functions of particle charge, applied potentials, feed velocity, diameter of electrodes, separation distance between electrodes, distance between collection plate and electrodes, etc. As such, the model is useful for designing PES units. Furtherwork is needed, however, to incorporate the effects of polarization of particles in an electric field.

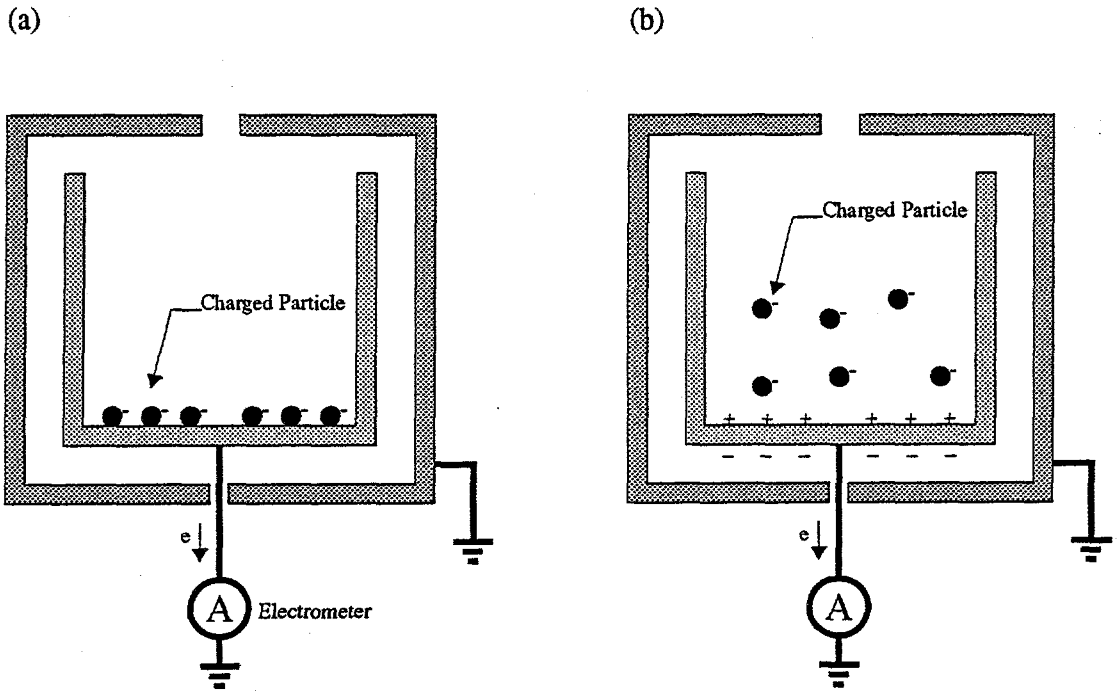

Figure 1. Schematic representation of the principles of particle charge measurement using a Faraday cage

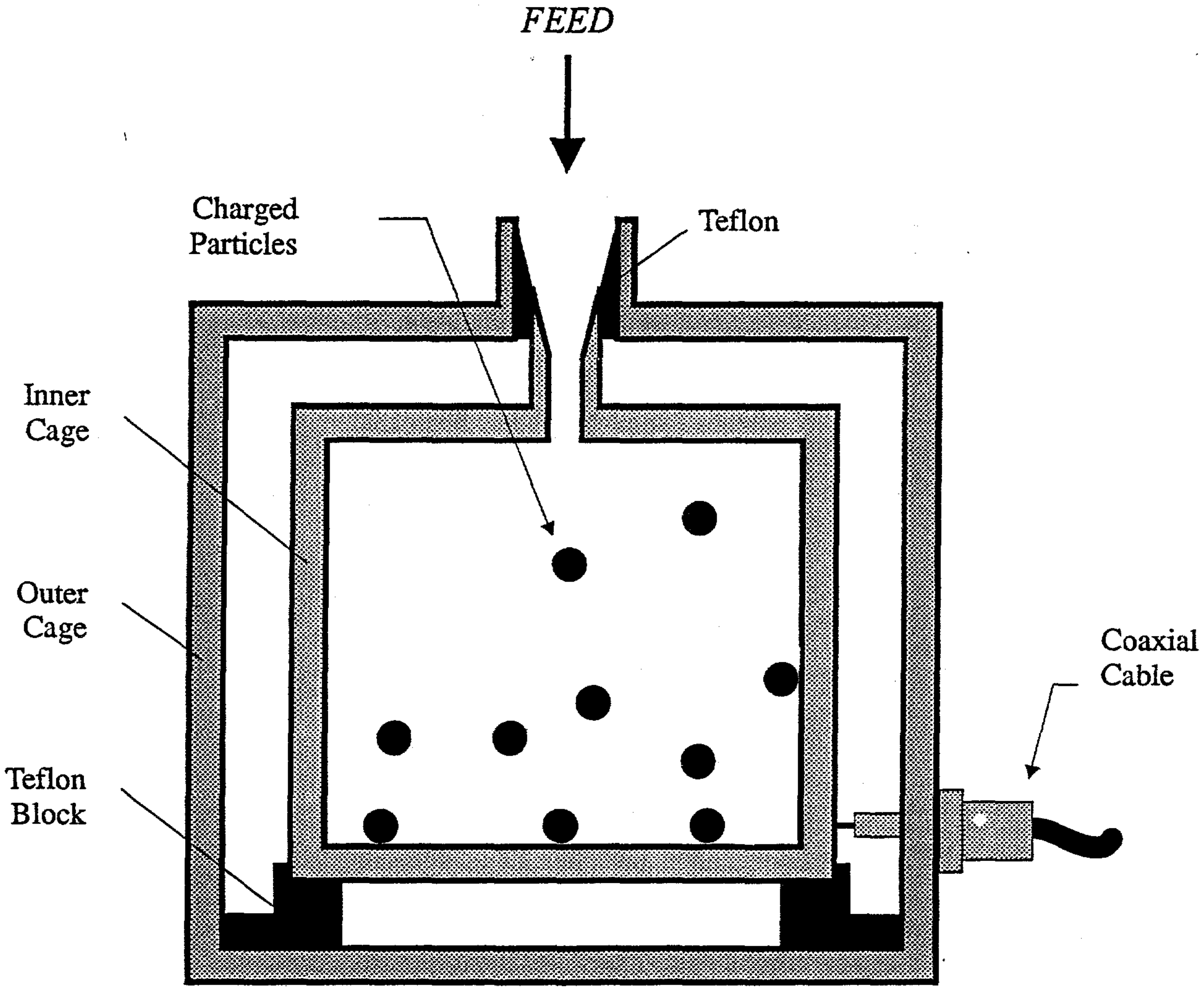

Figure 2. Schematic representation of the Faraday cage used in the present work

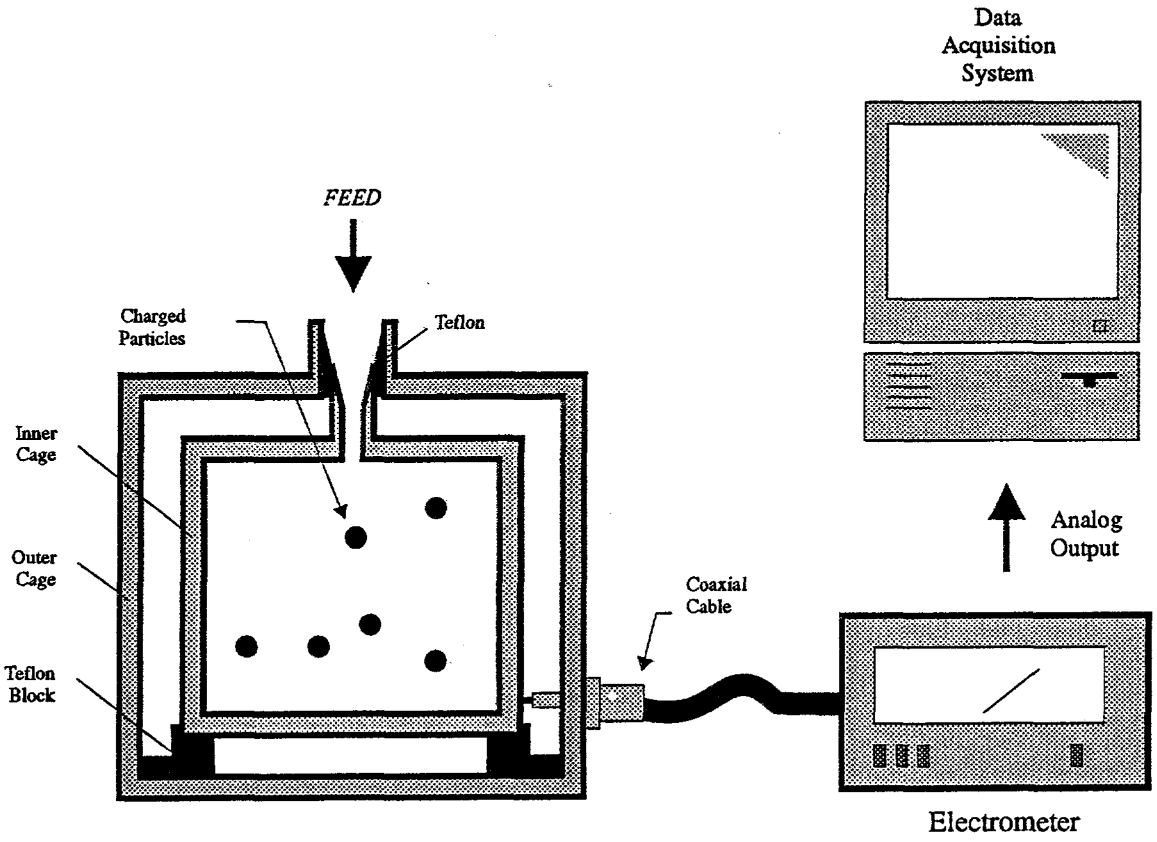

Figure 3. Instrumentation for the particle charge measurement using a Faraday cage

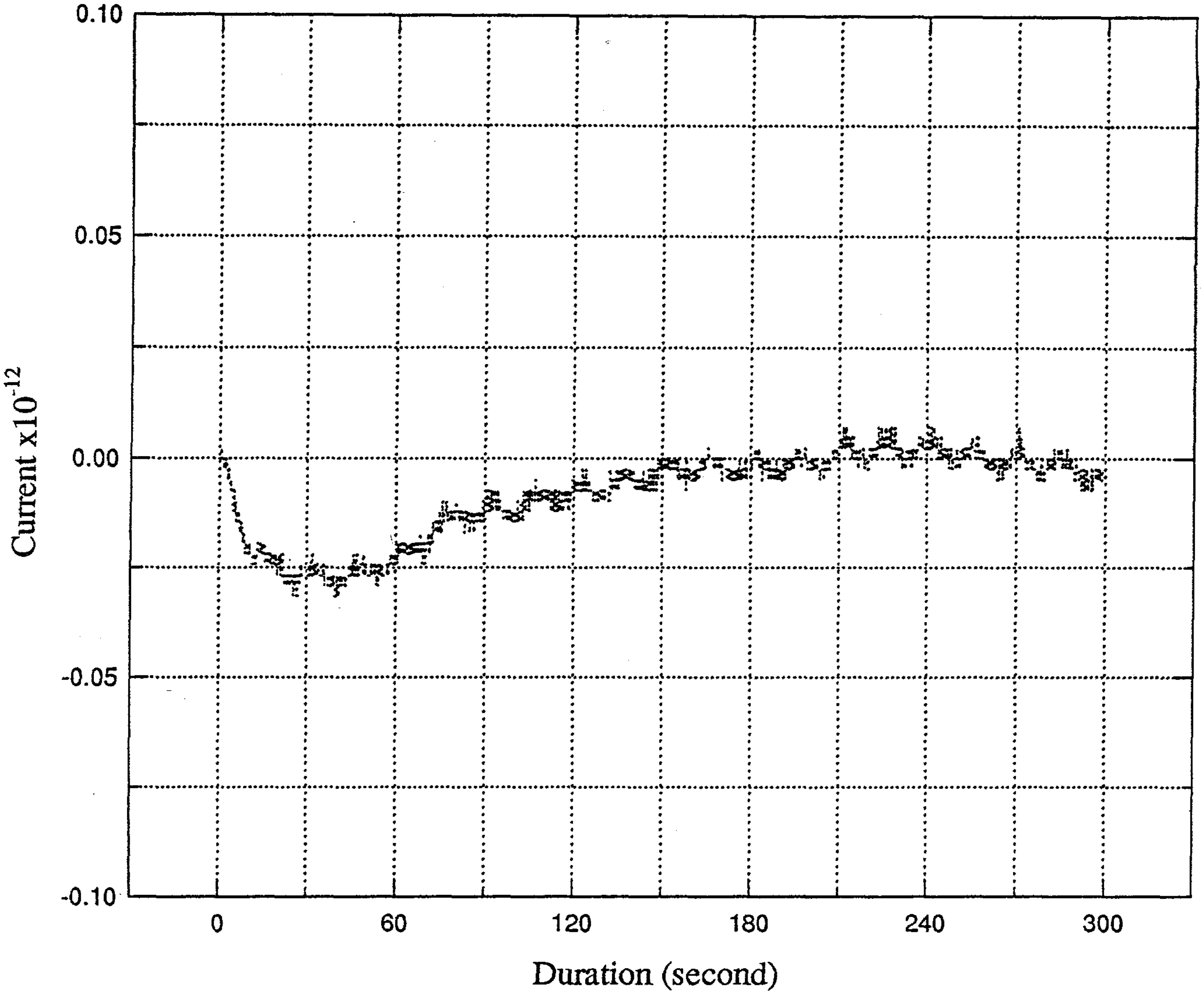

Figure 4. A printout from the data acquisition system used in conjuction with the Faraday cage. The result was obtained with a quartz sample (60μm)

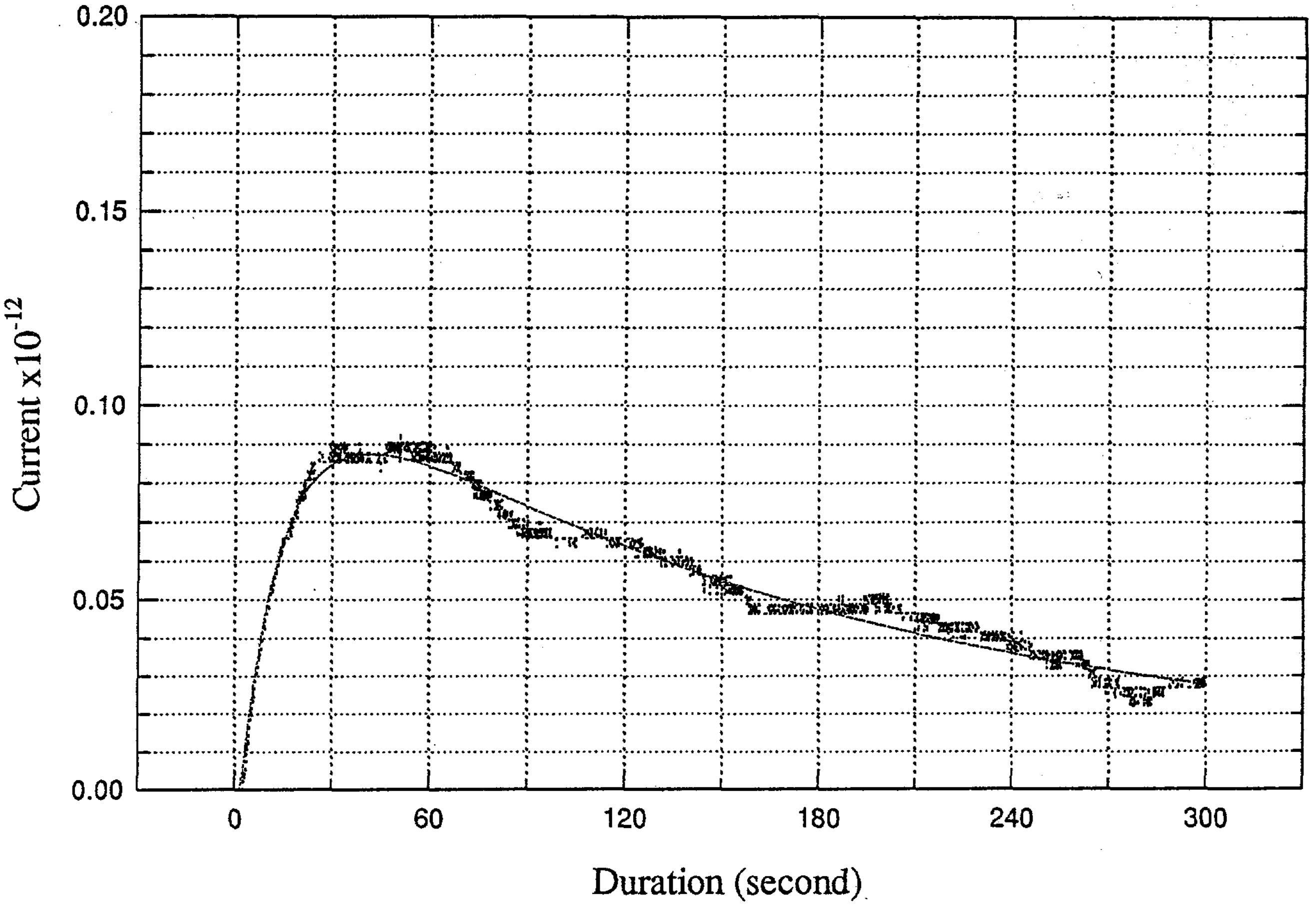

Figure 5. A printout from the data acquisition system used in conjuction with the Faraday cage. The result was obtained with a Pittsburgh No. 8 coal sample (+65 mesh)

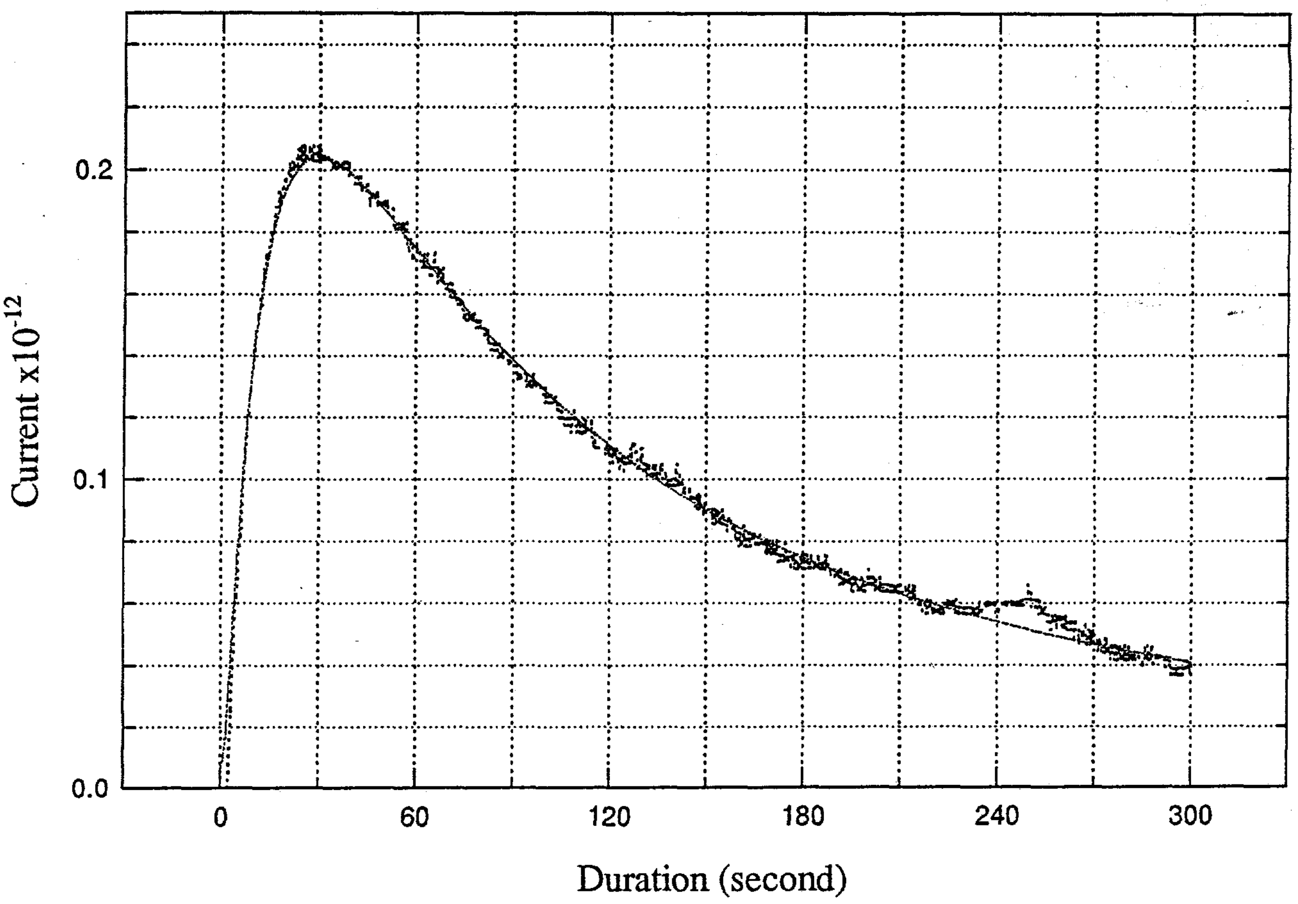

Figure 6. A printout from the data acquisition system used in conjuction with the Faraday cage. The result was obtained with a Pittsburgh No. 8 coal sample (-65 x 100 mesh)

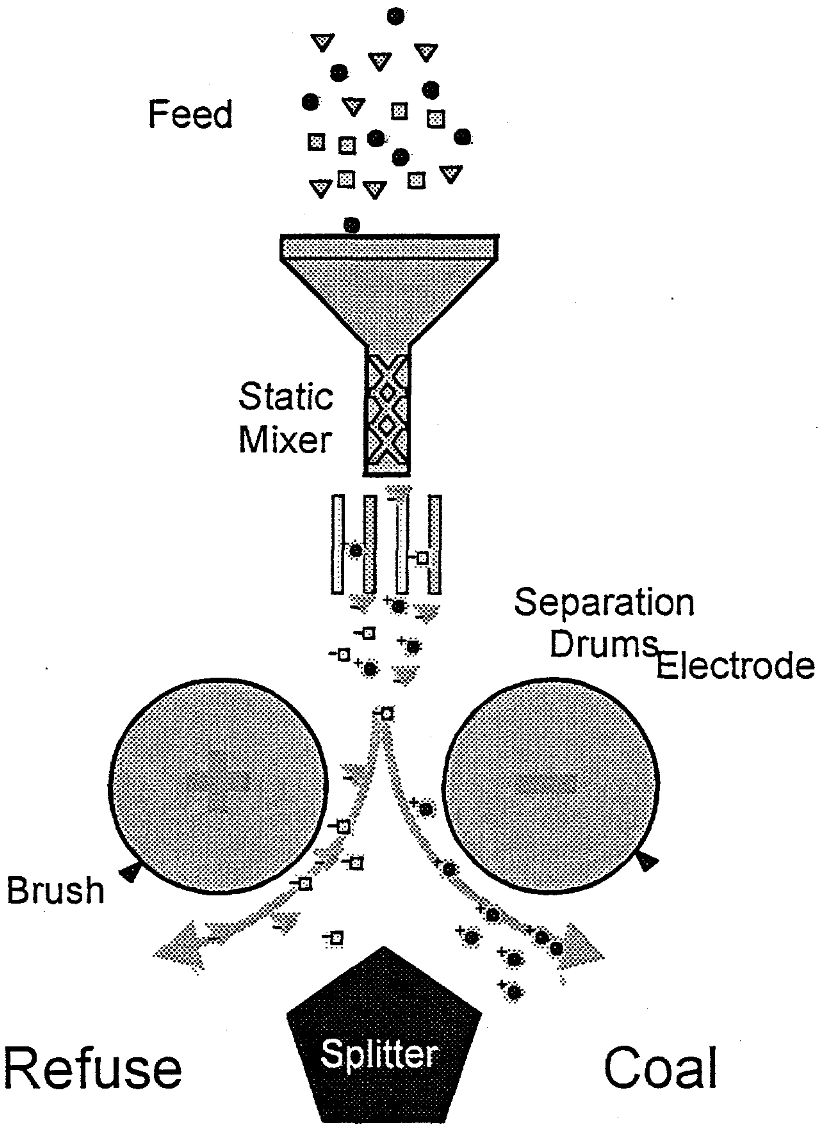

Figure 7. Schematic representation of the open-gradient triboelectrostatic separator used in the present work

Figure 8. Photograph of the bench-scale separator in construction

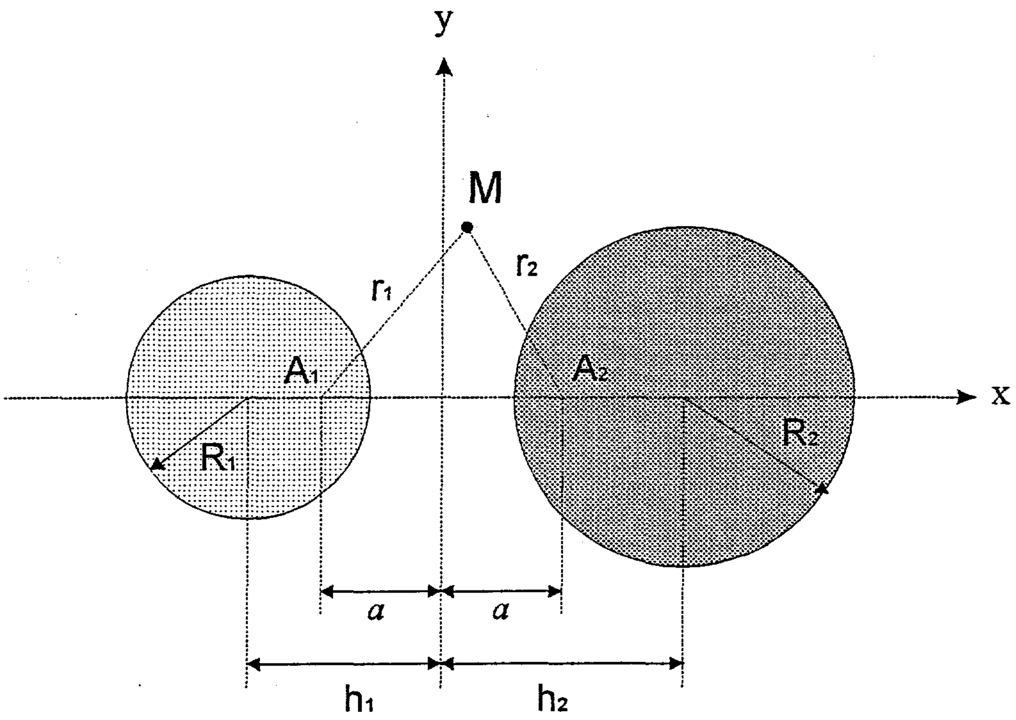

Figure 9. Calculation of the potential (φ) at point A in space in the non-uniform electric field created between cylindrical electrodes of radius R_1 and R_2. The charges of the electrodes are represented by the point charge (σ) at point A_1 and A_2

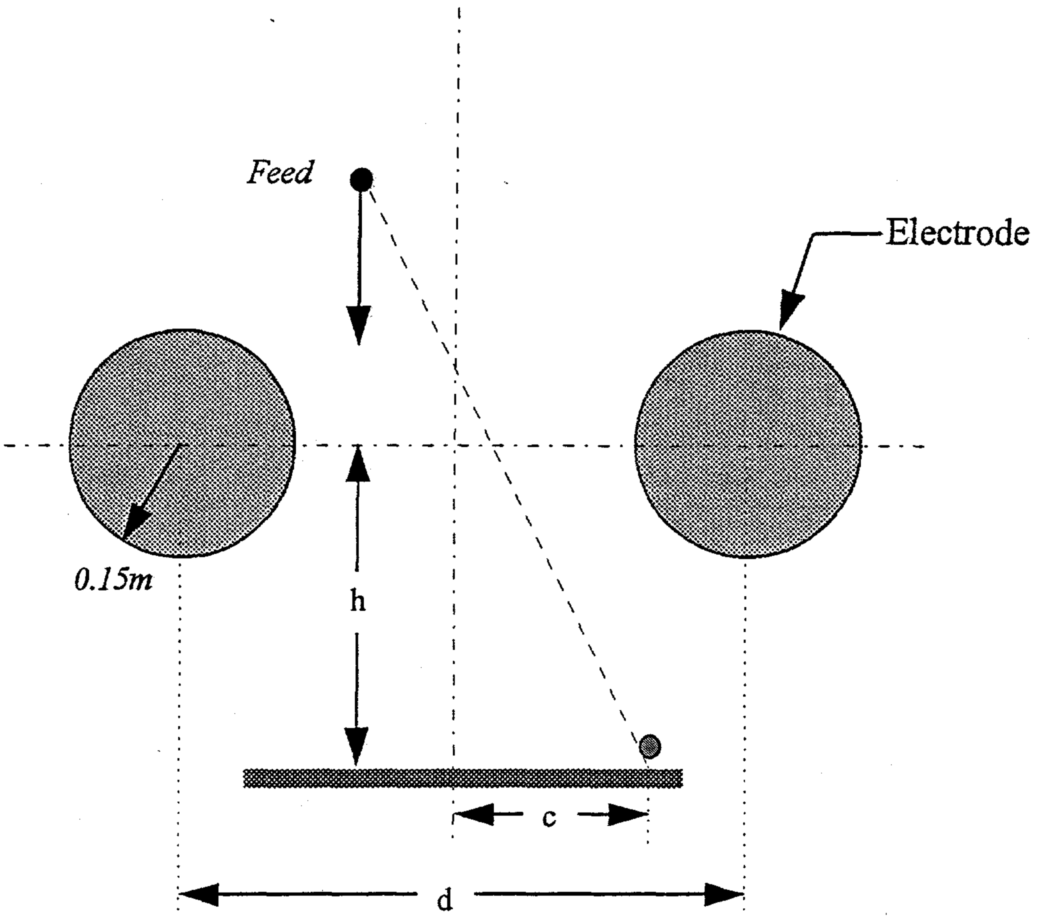

Figure 10. Movement of a charged particle in a non-uniform electric field created by cylindrical electrodes; a and b represent the original position, c represents deflection of the particle on the collection plate, and d represents the distance between the centers of the electrodes